Indonesian Journal of Forestry Research Vol. 4, No. 1, April 2017, 15-25 ISSN: 2355-7079/E-ISSN: 2406-8195

EFFECTS OF DRAINAGE DITCHES ON WATER TABLE LEVEL, SOIL CONDITIONS AND TREE GROWTH OF DEGRADED PEATLAND FORESTS IN WEST KALIMANTAN

Dwi Astiani[1*], Burhanuddin[1], Lisa M. Curran[2], Mujiman[3] and Ruspita Salim[3]

[1]Faculty of Forestry, University of Tanjungpura, Jl. Imam Bonjol Pontianak, West Kalimantan, Indonesia
[2]Stanford University, Y2E2 Building, Room 373-473, Ortega Stanford, CA 94305-2034 ,USA
[3]Lembaga Living Landscape, Pontianak, West Kalimantan, Indonesia

Received: 2 April 2016, Revised: 22 March 2017, Accepted: 27 March 2017

EFFECTS OF DRAINAGE DITCHES ON WATER TABLE LEVEL, SOIL CONDITIONS AND TREE GROWTH OF DEGRADED PEATLAND FORESTS IN WEST KALIMANTAN. Currently, tropical peatland forests are under considerable pressure because of increasing deforestation and degradation of forests. In Kalimantan, degradation and deforestation of peatland forests are driven primarily by industrial logging, expansion of agricultural activities through primarily conversion of forests to agricultural land and oil palm plantations. By the establishment of intensive drainage, it can induce wildfires in peatland. Unmanaged drainage ditches will alter water table levels within the site adjacent to the drainage including to surrounding peatland forest. Water table assessments were conducted before and after peatland drainage on 2007/2009 and 2012/2015 in Kubu Raya, West Kalimantan. This paper studies the effect of drainage ditches into the peat land water table. Results show the establishment of drainage ditches on this peatland landscape lowered the water table by more than 3 times from ~11.7 cm (SE = 1.5, n = 5) to ~37.3 cm (SE = 2.1 cm, n = 26). The effect on the water table was in drier months of July-August. Lowering the water table level altered worst the soil micro climate, peat temperature and peat water content. The results indicate the land use changes in peatland with the establishment of drainage affects peatland water table currently. In the area of less than 500 m from the drainage, the water level tends to lower toward the drainage feature. Therefore, recovery of peatland forests should be initiated by managing the landscape hydrology (i.e. water table) to restore the ecosystem and to protect the remaining peat swamp forest.

Keywords: Degraded peatland forest, drainage ditches, ecosystem restoration, soil micro climate, tropical peatland.

DAMPAK PARIT DRAINASE TERHADAP TINGGI MUKA AIR, KONDISI TANAH DAN PERTUMBUHAN POHON DI HUTAN GAMBUT KALIMANTAN BARAT. Saat ini, hutan gambut tropis berada di bawah tekanan yang cukup besar karena meningkatnya deforestasi dan degradasi hutan. Di Kalimantan, deforestasi dan degradasi hutan gambut terutama didorong oleh adanya industri penebangan, perluasan kegiatan pertanian terutama dari konversi hutan untuk lahan pertanian dan perkebunan kelapa sawit. Dengan pembangunan parit drainase intensif, hal ini dapat meningkatkan resiko kebakaran hutan. Drainase parit yang tidak dikelola dengan baik akan mengubah tinggi muka air di daerah sekitar drainase termasuk daerah di sekitar hutan gambut. Penelitian ini mempelajari pengaruh drainase terhadap perubahan air muka gambut. Pengukuran muka air dilakukan sebelum dan sesudah lahan gambut dikeringkan pada tahun 2007/2009 dan 2012/2015 di Kubu Raya, Kalimantan Barat. Hasil penelitian menunjukkan bahwa parit drainase pada lansekap lahan gambut menurunkan tinggi muka air lebih dari 3 kali, dari ~ 11,7 cm (SE = 1,5; n = 5) menjadi ~ 37,3 cm (SE = 2,1 cm; n = 26). Dampak tinggi muka air lebih buruk pada bulan kering (Juli-Agustus). Menurunnya tinggi muka air gambut mengubah iklim mikro tanah, terutama suhu dan kadar air gambut. Hasil penelitian menunjukkan bahwa perubahan penggunaan lahan di gambut bersamaan dengan pembangunan drainase akan mempengaruhi tinggi muka air gambut secara beragam. Pada jarak kurang dari 500 m dari drainase, tinggi muka

---

[*] Corresponding author: astiani.dwi@gmail.com, lmcurran@gmail.com, mjm.mujiman@gmail.com, pita.anzonk@gmail.com

doi: http://dx.doi.org/10.20886/ijfr.2017.4.1.15-25

air cenderung meningkat menuju ke arah drainase. Oleh karena itu, restorasi ekosistem hutan gambut harus dimulai dengan mengelola hidrologi lansekap.

Kata kunci: Hutan gambut terdegradasi, parit drainase, restorasi ekosistem, iklim mikro tanah, gambut tropis

I. INTRODUCTION

Tropical forests are under considerable pressure because of the raise of deforestation and degradation of intact forests (Hansen et al., 2001; Achard et al., 2002; Field, Werf, & Shen, 2009). The deforestation rates of intact forests in South-East Asian tropical peatlands – concentrated in Sumatra and Kalimantan, Indonesia – has been reported as 3.4% y^{-1} from 1990 to 2010 (Miettinen, Shi, & Liew, 2011), which exceeds the deforestation rates reported for other tropical forests such as in Central America and the Caribbean (1.2% y^{-1}) and South America (0.5% y^{-1}) (Achard et al., 2002; Hergoualc'h & Verchot, 2011). Currently, only 29% of the primary peatland forests of South-East Asia remain (Miettinen, Shi, & Liew, 2016). Tropical peatland accounts for 25% of deforestation from 2000 to 2005 in South-East Asia (Hooijer, Silvius, Wösten, & Page, 2006).

Large areas of tropical peatland forests have been logged for wood products to supply local, regional and global demand (Curran et al., 1999) and developed for either small-scale farming (e.g. sago, corn, pineapple, and vegetables) or large-scale agricultural plantations (e.g. oil palm) involving extensive drainage of peatlands, particularly in Indonesia (Achten & Verchot, 2011; Carlson et al., 2012, Carlson et al., 2013). These peatlands have also incurred synergistic exposure to drought and wildfires (Langner, Miettinen, & Siegert, 2007; Page, Hoscilo, & Tansey, 2008; Langner & Siegert, 2008). As a result of both natural and anthropogenic changes, deforested and drained tropical peatlands have become potential significant source of greenhouse gas (GHG) emissions globally as lowering the peatland water table leads to a significant increase of CO_2 emissions (Astiani, Mujiman, Salim, Hatta, & Firwanta, 2015; Astiani, 2016) as well as changes in peat soil characteristics. Deforestation and forest degradation of forest biomass and soil carbon have become truly global issues because of their contributions to global climate change (Werf et al., 2009; Eva et al., 2010). Werf et al. (2010) estimated that in 2005 deforestation accounted for about 20 - 29% of the total anthropogenic GHG emissions, primarily carbondioxide (CO_2).

In Indonesia, about 60% of the current emissions come from deforestation, degradation and peatland conversion (Someshwar, Boer, & Conrad, 2009). However, among carbon components, emissions and their corresponding environment factors from land-use and land-cover change are perhaps the most uncertain components of the global carbon cycle, with enormous implications for estimating the current carbon budget and for modelling scenarios of climate change over the next 10-50 years (Ramankutty et al., 2007; Carlson et al., 2012, Carlson et al., 2013). Because peatlands sequester relatively high carbon stocks – especially below ground – these forests may play an important role in moderating atmospheric CO_2 concentrations. However, forest degradation, land cover changes, and altered drainage, combined with changes in temperature and precipitation, are transforming peatland forests into major carbon sources rather than stores/sinks (Carlson et al., 2012, Carlson et al., 2013). Moreover, degradation of forest coverage is often a complex process with some degree of ecological recovery and a strong interaction with climatic fluctuations (Jones & Schmitz, 2009). Therefore, large uncertainties in land-based carbon stocks and fluxes exist and, in particular, from drained and degraded forested peatlands. Assessment of CO_2 respiration of

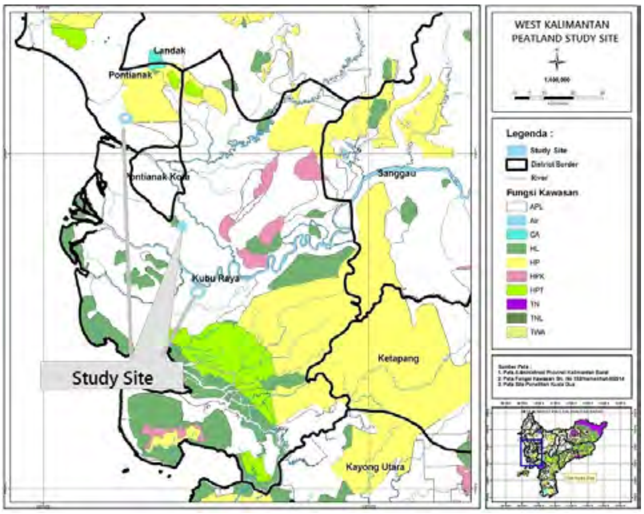


Figure 1. Study site of water level assessment

peat across a range of annual crops grown on peatland found a high CO_2 respiration from agricultural land uses on peat ranging from 83.8 to 139.9 ton ha^{-1} y^{-1} (Astiani, Hatta, & Fifian, 2015) and in drained, degraded peatland forest ~76 ton ha^{-1} y^{-1} (Astiani, 2014). However, the interactive effects of climate, water table, soil and site characteristics and forest conditions and dynamics are poorly understood. This paper studies the effect of drainage ditches on peatland water table, soil characteristics, and growth of degraded peatland forests in Kubu Raya District, West Kalimantan.

II. MATERIAL AND METHOD

2.1 Study Site

The study was conducted in a formerly logged peatland forest in an ombrotrophic, coastal peatland in Kubu Raya District, West Kalimantan, Indonesia. The plot is located at 0013' S and 109026' E, ca~ 4 m a.s.l. Mean annual rainfall is 3200 mm ± 530 mm (based on rainfall data on 2000-2014, recorded from West Kalimantan Supadio Station) with zero months per year with an average of less than 100 mm rainfall, even during the onset of the El Niño Southern Oscillation (ENSO). Average ambient temperature is 26.5±0.5°C, with minimum and maximum temperatures of 22.6 - 32.2°C. The study location is depicted in Figure 1.

This site of peatland forest was selected based on intensive survey and satellite image searching (Landsat ETM+, 30 m resolution) that showed unfragmented forest blocks representing degraded peatland forest in the area. Throughout the 12 ha area, peat depth was measured with a Russian Peat Corer (Aquatic Research Instrument) coupled with Garmin eTrek GPS readings, then peat depth distributions were mapped. At this focal site, peat depth ranged from 2.6 to 5.4 m. By applying a georeferencing technique, the peat depth area generated in ArcGIS was then clustered into three peat depth classes together with corresponding areas within the total measured area (<3.5 m ~ 6.5 ha; 3.5 – 4.5 m ~ 4.25 ha; and >4.5 m ~ 1.5 ha).

In 2009, the local government established canals/drainage ditches (3 m width x 2 m depth) for small scale agriculture and plantation development along the edges of the East and West sides of the peatland forest of our focal study site within a distance of approximately 300 m and 200 m parallel to both edges of the studied forest landscape. Water in the canals was not regulated by dams to maintain the water table (Figure 2). The water was drained into the lower part of the peatland landscape especially when there was no rain to the landscape. Therefore, tree growth before and after canal construction at the same site

(a) (b)

Figure 2. Peatland water table before (a) and post (b) canal establishment at the same landscape

could be compared. Observation over this peatland landscape concluded that there was no water level management following canal establishment.

2.2 Peatland Forest Floristic Condition and Tree Measurement

From previous studies, measurements have been conduced on the forest tree population within the forest block (Astiani, 2014; Astiani, Mujiman, et al., 2015; Astiani, Hatta, et al., 2015). This area was selectively logged (non-mechanized) in 2002-2004. Inventory estimated 12 trees per ha (> 30 cm dbh) were either removed or lost during felling over the site. Villagers interviewed near this area reported that vegetation coverage is mostly *Shorea* spp. (Dipterocarpaceae) and *Gonystylus* sp. (Thymeleaceae) for local construction. In 2007, Dipterocarpaceae comprised 7% of the understory (< 10cm dbh) and 3% of the canopy trees (≥10 cm dbh) (Astiani, 2014).

Mean stem density and tree basal area (> 10 cm dbh) yielded ~458 trees ha^{-1} and 9.73 m^{2}ha^{-1} and included at least 100 tree species within 31 families, whereas seedling (diameter <5 cm) and sapling (5-10 cm dbh) inventories recorded 25,390 ± 1433 seedlings ha^{-1} and 1113 ± 44.8 saplings ha^{-1}. The prominent species were *Litsea gracilipes* (Lauraceae), *Pometia pinnata* (Sapindaceae), *Litsea resinosa* (Lauraceae), *Tetramerista glabra* (Tetrameristaceae), *Elaeocarpus griffithii* (Elaeocarpaceae), *Litsea nidularis* (Lauraceae), *Shorea uliginosa* (Dipterocarpaceae) and *Neonauclea excelsa* (Rubiaceae). The forest vegetation registered for this study is important, because the aboveground vegetation could affect micro climate and hydrology balance within the forest under storey as well as belowground site characteristics.

Peatland forest condition within the study area is classified into low, mid and high degraded forest classes using projection results of the forest coverage percentages measured with Forest Densiometer. The forest coverage measurements were then cross checked with Leaf Area Index (LAI) measurements using Licor 2100 LAI measurement tool.

Across the study area, tree stems >10 cm dbh were mapped, tagged, identified to species or at least genus and monitored for diameter growth 3 years before and 3 years post canal establishment and compared. Stems (<10 cm dbh) were measured with a calliper and given a permanent red paint mark at the point of measurement. All stems >10 cm dbh were fitted with field-made steel dendrometer bands (Paoli, Curran, & Slik, 2008). Dendrometer bands were placed at 1.3 m above ground or 20 cm above buttresses and other bole irregularities. The red paint was renewed every six months to prevent visual loss if dendrometer bands were rotted or lost. Each tree was measured annually, and tree increment was calculated as the difference between diameter and estimated biomass at the end of each interval.

Transforming diameter increment into accurate biomass increment estimates requires application of an appropriate allometric equation (Clark et al., 2001). There are several available allometric equations for estimating biomass in tropical forest such as Kato, Tadak, and Ogawa (1978), Brown (1997) and Chave et al. (2005). In this study method stated by Paoli and Curran (2007) was applied to estimate aboveground biomass using the moist forest equation of Chave et al. (2005) who also incorporates specific wood densities. Chave et al.'s equation was derived from a larger data set than used by Brown (1997), and estimates aboveground biomass as a function of both diameter and wood specific density. Aboveground net tree biomass was defined as the cumulative growth of all trees that survived through each sampling interval (5-10; 10-20; and > 20 cm dbh; (Clark et al., 2001; Paoli & Curran, 2007). Moreover, new recruits from the 5-10 cm dbh class that grew into the >10cm dbh class was included.

2.3 Monitoring of Water Table Levels

The effect of the establishment of drainage ditches on lowering water table levels was measured within the forest before and after the establishment of the drainage ditches near the peatland in 2009, and repeated during 2012-2015. Since 2007, nine piezometers have been located across permanent plots where NPP, soil emission, carbon and other related topics were studied. The results of these studies have been published previously by Astiani (2014). Before drainage established water levels were monitored and observed monthly and more focus on dry and rainy months, while post drainage establishment, water table levels were monitored more intensively (weekly) over the years. The average of monthly water table within the forest and mean distribution of water table across the landscape among the drainage sites were accumulated.

2.4 Peat/Soil Environment Conditions

Along with other focus of the study on soil/peat CO_2 emissions using a Licor 8100 Automatics Soil CO_2 Respiration Measurement bi-weekly and it was averaged for monthly condition. Several site conditions at the same site before and after the drainage establishment such as soil surface temperature, content of soil surface water, and soil bulk density within 0-20 cm depth, for both conditions of water table levels. The first soil condition measurements were assessed concurrently with other observation on peat soil CO_2 emissions (Astiani, 2014) for both conditions of water table levels in 2008 and 2011 consecutively.

2.5 Data Analysis

Throughout this paper, data are presented as means and standard errors (SE) unless otherwise noted. Trees within a plot were grouped into three size classes (i.e., 5-10, 10-20, >20 cm dbh) and growth of all stems within a size class were summed. Comparisons among the 3 years before and 3 years post canal-establishment on water table levels, soil characteristics, and tree measurements were examined with simple T test if growth, productivity, and tree mortality and all those variables differed significantly across the two conditions. All analyses were performed using Sigmaplot version 11.2.

III. RESULT AND DISCUSSION

3.1 Influence of Drainage Ditches on Peatland Water Table Levels

The establishment of drainage ditches lowered the water table across the overall peatland landscape. The results of measurements demonstrate that water table level depths have significantly lowered after the establishment of the drainage ditches adjacent to the ombrotrophic peatland forest. T test results demonstrate that both situations, before and after ditches were significantly different ($t = -9.991$, $df = 2$, $P = <0.001$) (Figure 3). The results of the overall yearly monthly assessments shows that mean of water level depth before the

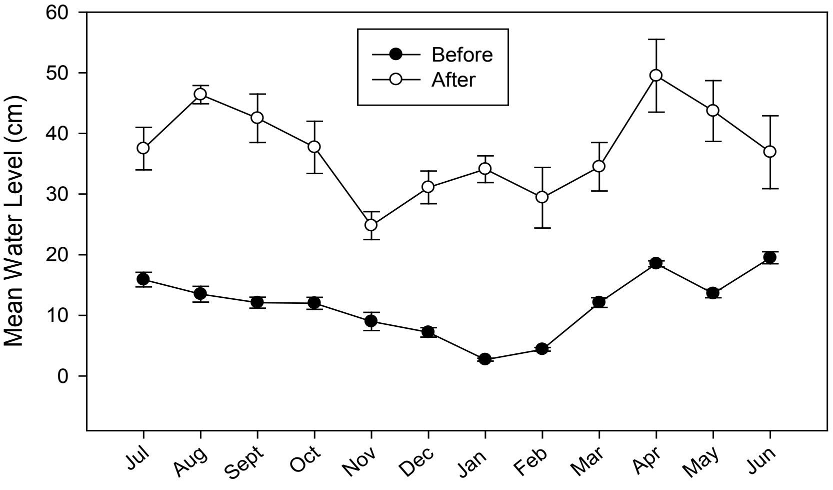


Figure 3. Distribution of mean water table level on peatland before and after the establishment of drainage ditches/canals

establishment of the drainage ditches was 11.7 ± 1.5 cm, while after the canal construction it was 37.3 ± 2.1 cm. Even though the shift of water table was varied at each point of assessment, the canal lowered the landscape mean water table by ~25 cm.

Figure 3 demonstrates that post drainage establishment, mean monthly water table level of the peatland landscape fluctuated more and significantly increased according to the the distance of water level below the peatland surface. Lower water table consequently impacted on the other conditions or characteristics of the peatland site as stated by Mitsch and Gosselink (1993), peatland hydrology has an influence on peatland chemical and biotic characteristics and processes as well as influencing land formation through their interaction with vegetation, nutrient dynamics, and carbon fluxes (Waddington & Roulet, 1997). Hydrological changes will also alter the rate of gas diffusion and carbon flows (Holden, 2005).

3.2 Peat Characteristics Before and After Establishment of the Canals

Some soil conditions were observed before and post establishment of the ditches. Results indicated that there was significant difference in soil surface temperature. The mean monthly distribution of soil temperature is presented in Figure 4a. Results of a T test indicated that the temperature before the presence of the canal was relatively lower than post canal (t = -3.78; df = 47; P = <0.001). Results show that peat temperature was consistently higher during post canal establishment. Higher differences were observed especially in dry and rainy months of July - August and December - January whereby in dry months, the temperature post canal could reach 37-38°C, while before it was 3-4°C lower. Moreover, in rainy months post canal temperature was consistently higher than before. Overall monthly means were 29.9 °C and 31.8°C before and after the drainage establishment. There was also significant difference in the peat surface water content (t = 21.23; df = 52; P = <0,001). Peat surface (0-20 cm) water content was significantly higher before the presence of the ditches (94.6% ± 0.8 vs 77.7% ± 0.2). The mean monthly distribution of water content is depicted in Figure 4b.

It was also observed that when water table lowered (Figure 5a), the water content also decreased (p = <0.001). Meanwhile since the peatland landscape is solely rainfed the water table was mainly influenced by the precipitation (Figure 5b.).

Here the presence of soil water with higher water level close to peat surface could mitigate

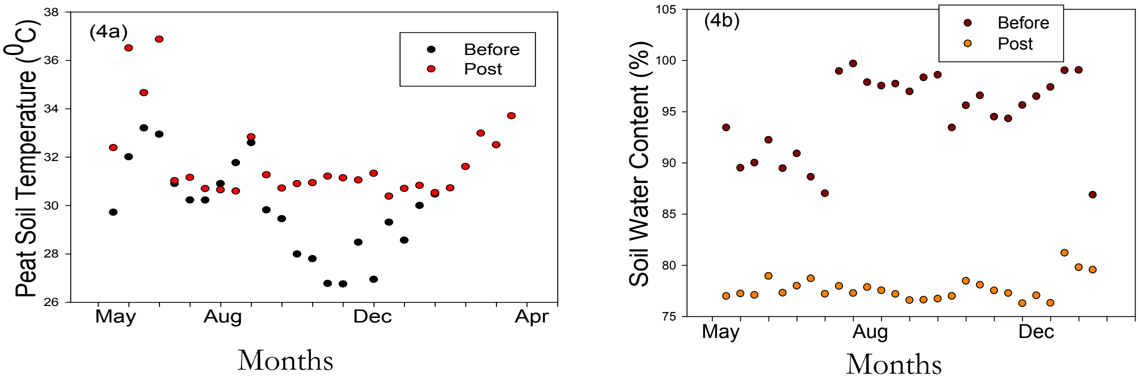


Figure 4. Mean soil temperature on forest floor before and post establishment of canals (4a); Mean monthly soil water content before and post establishment of drainage ditches (4b)

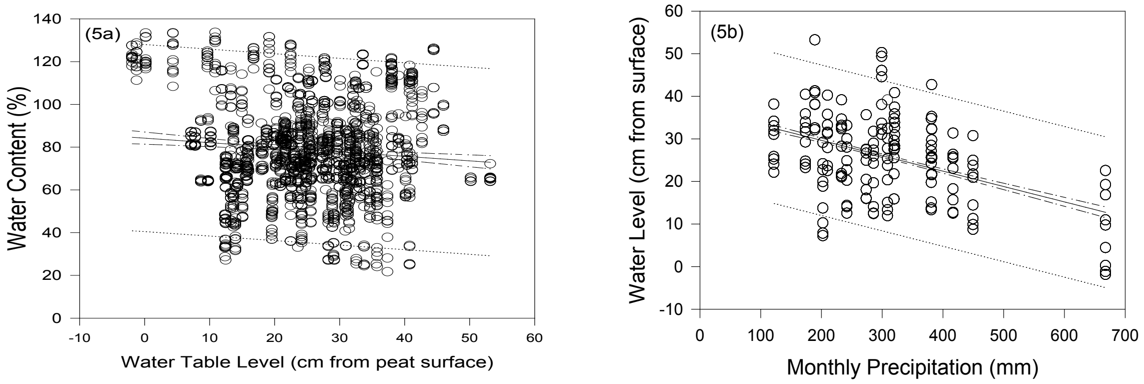


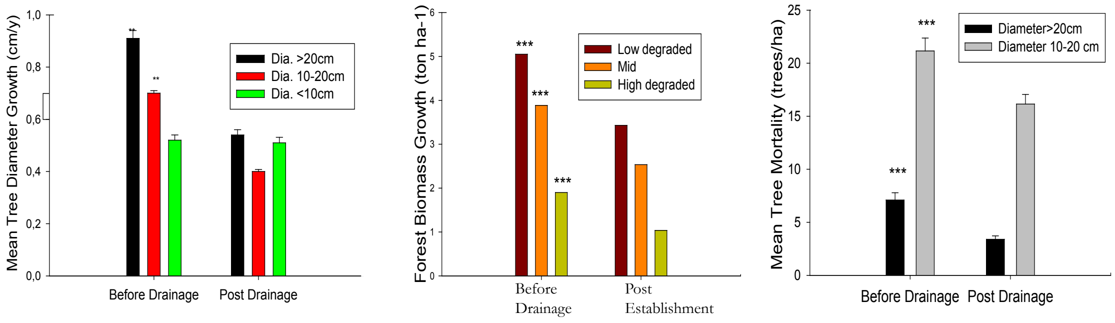
Figure 5. Linear regression between peatland water level and peatland 15 cm-surface water content (a); (5b) Linear regression between monthly precipitation and peatland water table (b)

soil temperature escalation. Figures 4a and 4b, show constant water content reduction which could be one of the factors that leads to the rise of soil temperature.

3.3 Effects of Canal/Drainage Ditches on Forest Dynamics

Comparison of diameter growth and tree biomass per hectare of trees with diameter >10cm demonstrated that lowering water table levels due to drainage ditches has significantly affected mean diameter growth and total biomass per hectare in this degraded peatland (~42% decrease in tree diameter >20 cm and diameter 10-20 cm, $p = <0.001$). However, for smaller trees (diameter < 10 cm) there is no significant difference in their annual growth rates (Figure 6a) and trees seem to grow better in its new condition after the changing of water table levels. Although this degraded peatland forest varies in its biomass stock, tree growth and mortality, lowering water table levels constantly decreased the tree growth at different levels of forest degradation (Figure 6b). However, an interesting result is shown in lowering the water table level significantly and reducing the mortality of trees (Figures 6c).

Associated demographic shifts in this study area included increased tree growth and recruitment of small trees, increases in aboveground biomass, lowering mortality of smaller trees, yet increased large tree mortality. The changes of biomass, growth, and mortality of trees could reflect a distribution of responses



(a) (b) (c)

Figure 6. The average of tree diameter growth (cm per tree) of tree diameter >20 cm and 10-20 cm before and post drainage (a); biomass growth at some levels of degradation (b) (***=significantly different at p = <0.001); Mean annual tree mortality per ha before and post drainage (c)

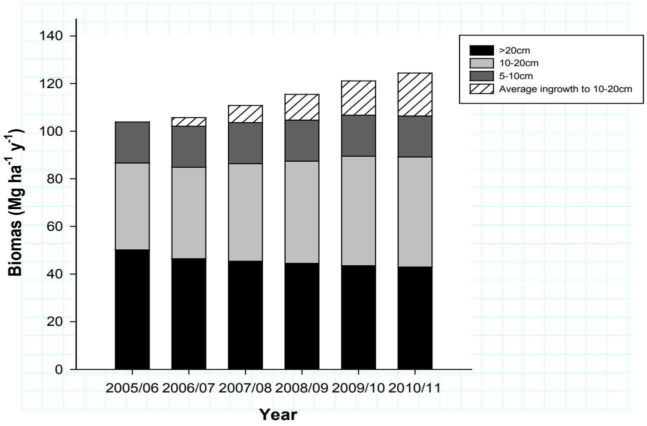


Figure 7. Biomass growth per ha in degraded peatland forest 2005-2011
Source: Astiani (2014)

to resource availability and site condition dynamics (Feeley et al., 2007) and diversity shifting (Astiani, 2016). Our previous study demonstrated that reduced rainfall in peatlands lowered the water table (R= -0.44) from the peat surface (Astiani, 2014) which has been demonstrated to have positive effects on Net Primary Production in some northern peatlands (Laiho & Laine, 1997; Minkkinen, Korhonen, Savolainen, & Laine, 2002; Laiho, Vasander, Penttilä, & Laine, 2003).

Even though lowering of the water table level due to the establishment of drainage ditches reduced the biomass growth of the trees, when we calculated cumulatively within the six years of assessments (before and post canal presence) it showed that a significant additional growth occurred, whereby stand basal area of trees increased by 27%. More detailed analysis indicated that the biomass of larger trees decreased by about ~ 14%, but growth of smaller and younger trees increased by ~ 76%. Previous analysis showed that the overall forest biomass increased by ~24% (Figure 7), therefore, the results indicated that drainage establishment has affected this secondary, degraded peatland forest by tending to reduce the growth of larger trees, yet had no impact on the growth of smaller trees while also reducing their mortality level.

These results demonstrate the impacts of the establishment of drainage ditches on hydrology and forest dynamics of degraded peatland forest. Peatland forest should be maintained in a landscape based on management to enhance their sustainability and natural resource functions. Partial management of this ecosystem could interfere with the peatland forest's multi roles not only in supporting sustainable wood and food production, but also its important contribution in mitigating GHG emissions.

Hydrological restoration is urgently needed to take care of the affected forests in order to rehabilitate the ecological functions of these peatland forests and to support their sustainability. Future research is needed to understand the most suitable peatland water table for peatland forest and other land covers to support peatland restoration and conservation.

IV. CONCLUSION

Establishment of drainage ditches/canals in the opened/agricultural peatland landscape decreased peatland water table levels in the area. However, it had significant effect on stand growth in nearby peatland forests within the same landscape, even though the peatland forests themselves were not changed to other land uses.

Decreasing water table levels in the forest reduced tree growth rate individually especially for larger trees (diameter>20 cm) yet concurrently reduced their rate of tree mortality. These results imply that management of degraded peatland forests has to focus more on attention to forest land cover and land use changes (e.g. to small and large scale agriculture, plantation, or other purposes) in the peatland surrounding the forest, especially their effects on the alteration of the hydrological conditions which influence tree growth and mortality within the forest ecosystem. A well-managed water level (e.g. maintained by overflow dams) is urgently needed for the affected forests in order to restore the ecological functions of the forest and to support forest growth, health, and sustainability.

ACKNOWLEDGEMENT

Thanks to people of Kampung Parit H Ali and Kampung Jawa Kubu Raya, West Kalimantan Indonesia for their support in the works surrounding their communities. We are also thankful to NASA and Yale University which funded our previous intensive study on peatland in West Kalimantan and made continuiting of the study easier. Our appreciation is given to Tanjungpura University and Balai Pengkajian Industri Departemen Perdagangan Pontianak in Indonesia for allowing team to work in their laboratorium. Special thanks to LLI staffs in Pontianak (Dessy Ratnasari, Nelly Lisnawati, Yadi Purwanto, Supardi, Umar) and others for their help to accomplish this work.

REFERENCES

Achard, F., Eva, H. D., Stibig, H., Mayaux, P., Gallego, J., Richards, T., & Malingreau, J. (2002). Determination of the world's humid tropical deforestation rates during the 1990's methodology and results of the TREES-II research programme. *TREES Publications Series B, Research Report No.5*. European Commission, Directorate General Joint Research Centre, Institute for Environment and Sustainability.

Achten, W. M. J., & Verchot, L. V. (2011). Implication of bio-diesel induced land-use change for CO_2 emissions: Case study in tropical America, Africa, and Southeast Asia. *Ecology and Society*, *16*(4). doi://dx.doi.org/10.5751/ES-04403-160414.

Astiani, D. (2014). *Bornean peatlands: Forest dynamics, land use and carbon flux*. (Doctoral Dissertation). Graduate School of Yale University, USA. Retrieved from Proquest (UMI no 3580626)

Astiani, D., Hatta, M., & Fifian, F. (2015). Soil CO_2 respiration along annual crops or land-cover type gradients on West Kalimantan degraded peatland forest. *Procedia Environmental Sciences*, *28*,132–141.doi://doi.org/10.1016/j.proenv.2015.07.019.

Astiani, D., Mujiman, Salim, R., Hatta, M., & Firwanta, D.D. (2015). Tropical peatland forest degradation: Effects on forest regeneration biomass, growth, mortality, and forest microclimate conditions. In I. Azhar R. Hartono, A. H. Iswanto, K. S. Hartini, A. Susilowati, D. Elfiati, Muhdi (Ed.), *Proceeding the 6th International Symposium of Indonesian Wood Research Society* (pp. 162–169). Indonesian Wood Research Society (IWoRS), Bogor.

Brown, S. (1997). Estimating biomass and biomass change of tropical forests: A primer. Rome: UN FAO *Forestry Paper 134*. Food and Agriculture Organization.

Carlson, K.M., Curran, L.M., Asner, G.P., Pittman, A.M., Trigg, S.N., & Adeney, J.M.(2013). Carbon emissions from forest conversion by Kalimantan oil palm plantations. *Nature Climate Change*, *3*(3), 283–287. doi:10.1038/nclimate1702

Carlson, K.M., Curran, L.M., Ratnasari, D., Pittman, A. M., Soares-Filho, B. S., Asner, G. P., … Rodrigues, H. . (2012). Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. *PNAS 109*, 7559–7564.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., … Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, *145*(1), 87–99. doi:10.1007/s00442-005-0100-x

Clark, D.A., Brown, S., Kicklighter, D.W., Chambers, J.Q., Thomlinson, J.R., & Ni,J. (2001). Measuring net primary production in forests: Concepts and field methods. *Ecological Applications*, *11*(2), 356–370. doi:10.2307/3060894

Curran, L. M., Caniago, I., Paoli, G. D., Astianti, D., Kusneti, M., Leighton, M., … Haeruman, H. (1999). Impact of El Niño and logging canopy tree recruitment in Borneo. *Science*, *286*(5447), 2184–2188. doi://10.1126/science.286.5447.2184

Eva, H., Carboni, S., Achard, F., Stach, N., Durieux, L., Faure, J.-F., & Mollicone, D. (2010). Monitoring forest areas from continental to territorial levels using a sample of medium spatial resolution satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(2), 191–197. doi:10.1016/j.isprsjprs.2009.10.008

Feeley, K.J., Davies, S.J., Ashton, P.S., Bunyavejchewin, S., Supardi, M.N.N., Kassim, A. R., … Chave, J. (2007). The role of gap phase processes in the biomass dynamics of tropical forests. *Proceedings. Biological Science.*, *274*(1627), 2857–2864. doi:10.1098/rspb.2007.0954

Field, R. D., Werf, G. R. van der, & Shen, S. S. P. (2009). Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nature Geoscience*, *2*, 185–188. doi:10.1038/ngeo443

Hansen, A. J., Neilson, R. P., Dale, V. H., Flather, C. H., Iverson, L.R., Currie, D.J., … Bartlein, P.J. (2001). Global change in forests: responses of species, communities, and biomass. *BioScience*, *51*(9), 765. doi:10.1641/0006-3568(2001)051[0765:GCIFRO]2.0.CO;2

Hergoualc'hK., & Verchot, L. V. (2011). Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review. *Global Biogeochemical Cycles*, *25*, 1–13. doi:10.1029/2009GB003718

Holden, J. (2005). Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions of the Royal Society A Mathematical, Physical and Engineering Science*, *363*, 2891–2913. doi:10.1098/rsta.2005.1671

Hooijer, A., Silvius, M., Wösten, H., & Page, S. . (2006). PEAT-CO_2, Assessment of CO_2 emissions from drained peatlands in SE Asia. *Delft Hydraulics report Q3943*.

Jones, H. P., & Schmitz, O. J. (2009). Rapid recovery of damaged ecosystems. *PLos ONE*, *4*(5), e5653. doi:10.1371/journal.pone.0005653

Kato, R., Tadak, Y., & Ogawa, H. (1978). Plant biomass and growth increment studies in Pasoh forest. *Malaysia Nature Journal*, *30*, 211–224.

Laiho, R., & Laine, J. (1997). Tree stand biomass and carbon content in an age sequence of drained pine mires in southern Finland. *Forest Ecology and Management*, *93*(1–2), 161–169. doi:10.1016/S0378-1127(96)03916-3

Laiho, R., Vasander, H., Penttilä, T., & Laine, J. (2003). Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. *Global Biogeochemical Cycles*, *17*(2), 1–17. http:10.1029/2002GB002015

Langner, A., Miettinen, J., & Siegert, F. (2007). Land cover change 2002–2005 in Borneo and the role of fire derived from MODIS imagery. *Global Change Biology*, *13*(11), 2329–2340. doi:10.1111/j.1365-2486.2007.01442.x

Langner, A., & Siegert, F. (2008). Spatiotemporal fire occurrence in Borneo over a period of 10 years. *Global Change Biology*, *15*(1),48–62. doi:10.1111/j.1365-2486.2008.01828.x

Miettinen, J., Shi, C., & Liew, S. C. (2011). Influence of peatland and land cover distribution on fire regimes in insular Southeast Asia. *Regional Environmental Change*, *11*(1), 191–201. doi:10.1007/s10113-010-0131-7

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, *6*, 67–78. doi:10.1016/j.gecco.2016.02.004

Minkkinen, K., Korhonen, R., Savolainen, I., & Laine, J. (2002). Carbon balance and radiative forcing of Finnish peatlands 1900–2100 – the impact of forestry drainage. *Global Change Biology*, *8*(8), 785–799. doi:10.1046/j.1365-2486.2002.00504.x

Mitsch, W., & Gosselink, J. (1993). *Wetlands*. New York: Van Nostrand Reinhold.

Page, S., Hoscilo, A., & Tansey, K. (2008). Wildfire effects on tropical peatlands. *Geophysical Research Abstracts*, *10*.

Paoli, G. D., & Curran, L. M. (2007). Soil nutrients limit fine litter production and tree growth in mature lowland forest of Southwestern Borneo. *Ecosystems*, *10*(3), 503–518. doi:10.1007/s10021-007-9042-y

Paoli, G. D., Curran, L. M., & Slik, J. W. F. (2008). Soil nutrients affect spatial patterns of aboveground biomass and emergent tree density in southwestern Borneo. *Ecologia*, *155*(2), 287–299. doi:10.1007/s00442-007-0906-9

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A., & Houghton, R.A. (2007). Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biology*, *13*(1), 51–66. doi:10.1111/j.1365-2486.2006.01272.x

Someshwar, S., Boer, R., & Conrad, S. (2009). Managing peatland fire risk in central Kalimantan, Indonesia. *World Resources Report*, Washington DC.

Waddington, J. M., & Roulet, N. T. (1997). Groundwater flow and dissolved carbon movement in a boreal peatland. *Journal of Hydrology*, *191*(1–4), 122–138. doi:10.1016/S0022-1694(96)03075-2

Werf, G.R. van der, Morton, D.C., DeFries, R.S., Olivier, J.G.J., Kasibhatla, P.S., Jackson, R.B., … Randerson, J.T. (2009). CO_2 emissions from forest loss. *Nature Geoscience*, *2*, 737–738. doi:10.1038/ngeo671

Werf, G.R. van der, Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., … Leeuwen, T. T. van. (2010). Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmospheric *Chemistry Physics Discussion*, *10*, 11707–11735. doi:10.5194/acp-10-11707-2010